A Review of Groundwater-Surface Water Connectivity in the Cockburn Alluvium Management Zone

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1. Introduction and Purpose

Groundwater in the Cockburn River Alluvium Management Zone (Cockburn Zone) is managed under rules set out in the Water Sharing Plan for the Peel Valley Regulated, Unregulated, Alluvium and Fractured Rock Water Sources 2010 (the Plan) (NOW, 2010a). The Plan includes rules that restrict access to groundwater (cease-to-pump) relating to the height (and flow) of the Cockburn River. Groundwater licence holders within the Cockburn Zone have asked the Department of Industry – Water (DoI-W) to review those rules, specifically investigating the following three issues:

1. Provide evidence that support the concept that groundwater in the alluvial aquifer is highly connected to the surface water of the Cockburn River;
2. Demonstrate the potential impacts of continued groundwater pumping on surface water flows in the Cockburn River at times when surface water access has ceased;
3. Investigate possible alternative cease-to-pump trigger points to the Kootingal Bridge river gauge that may provide a more appropriate groundwater cease-to-pump reference point.

This report documents the review undertaken and the conclusions reached.

2. Water Management in the Peel and Cockburn Valleys

2.1. Water Policy

Consistent with national water policy, the NSW Government has adopted a number of policy principles to enable the hydraulic connectivity between aquifers and rivers to be considered in the management of connected water sources. These principles and how they have been applied in the development of Water Sharing Plans across NSW, including the Peel Water Sharing Plan, are explained in detail in "*Macro water sharing plans – the approach for groundwater a report to assist community consultation*" (NOW 2015). The principles are summarised below:

> *Principle 30 – Connectivity between groundwater sources and surface water is considered when setting access rules to limit the impacts of groundwater pumping on surface water flows.*
>
> *Principle 31 – 'Highly connected' systems for the purposes of applying management rules are defined as those systems where 70 percent or more of the groundwater extraction volume is derived from surface water within an irrigation season. All other systems are considered 'less highly connected'.*
>
> *Principle 32 – For management purposes, highly connected alluvial groundwater sources and their associated river reaches are classified as regulated, perennial or non-perennial to determine the type of management rules required.*
>
> *Principle 33 – Alluvial groundwater systems that are highly connected to perennial unregulated systems have specific rules that recognise the level of connectivity based on daily access linking their management to the associated unregulated surface water daily access rules. Non-perennial systems will have groundwater only rules.*

These principles guide the setting of appropriate rules to manage connectivity and are tailored for each water source. Management rules aim to balance the need to limit negative impacts on the river whilst still allowing access to the groundwater storage.

2.2. The Water Sharing Plan

The Water Sharing Plan for the Peel Valley Regulated, Unregulated, Alluvium and Fractured Rock Water Sources 2010 (the Plan) (NOW, 2010a) commenced on the 1 July 2010. The Plan establishes rules for sharing water between the environment and water users to ensure the resources and dependent ecosystems are sustainable in the long term.

The hydraulic connection between the Peel Alluvium Water Source (Peel Alluvium) and associated surface water is recognised in the Plan by rules that link groundwater access to that of the associated surface water source.

The Peel Alluvium is divided into seven management zones. Daily access rules link groundwater access to the surface water flow in a number of management zones, including the Cockburn Zone. These rules were incorporated into the Plan to protect low flows and remnant pools during dry seasons. The location of the Cockburn Zone is shown in **Figure 1.**

2.3. Plan Rules for Groundwater Access in the Cockburn Zone

The surface water-groundwater system of the Cockburn Zone meet all three physical criteria defined by DoI Water (Barrett and Broadstock, 2010) to be classified as a ‘highly-connected’ system for the purpose of applying management rules under the Plan (see Principle 31 above). That is:

- The water table is sufficiently shallow for the aquifer to be hydraulically connected to the river/creek bed, either as a losing or gaining stream.
- The average saturated thickness of the aquifer is no more than 30m.
- The average width of the alluvial aquifer is no more than 4km.

Additionally, although the Cockburn River does cease to flow, pools within the river are maintained by the groundwater base flows, and it was considered a perennial river in the context of considering plan rules.

To manage the potential impact of groundwater pumping on the Cockburn River during low flows, the Plan links daily access rules for groundwater pumping similar to the surface water cease to pump rules, but with a 28 day delay from when the trigger is reached and applied to surface water users.

The Plan establishes a cease-to-pump trigger for surface water users when river levels reach and fall below 0.25m at the Kootingal Bridge Gauging Station (GS419099). At the commencement of the Plan, this corresponded to the 84th percentile of all daily flow and a discharge volume of 2.6 ML/day (NOW 2010a).

The cease to pump rule for groundwater licence holders is triggered when the river height is 0.25 m or below for 28 consecutive days (NOW 2010b).This delay is a concession that recognises that the storage capacity of the aquifer provides some short-term temporal buffer to impacts on river baseflows.

The river height-to-flow rating has changed significantly since the Plan commencement due to a combination of bed movement and the longer period of recorded data now available. The issue is explored further in Section 5.

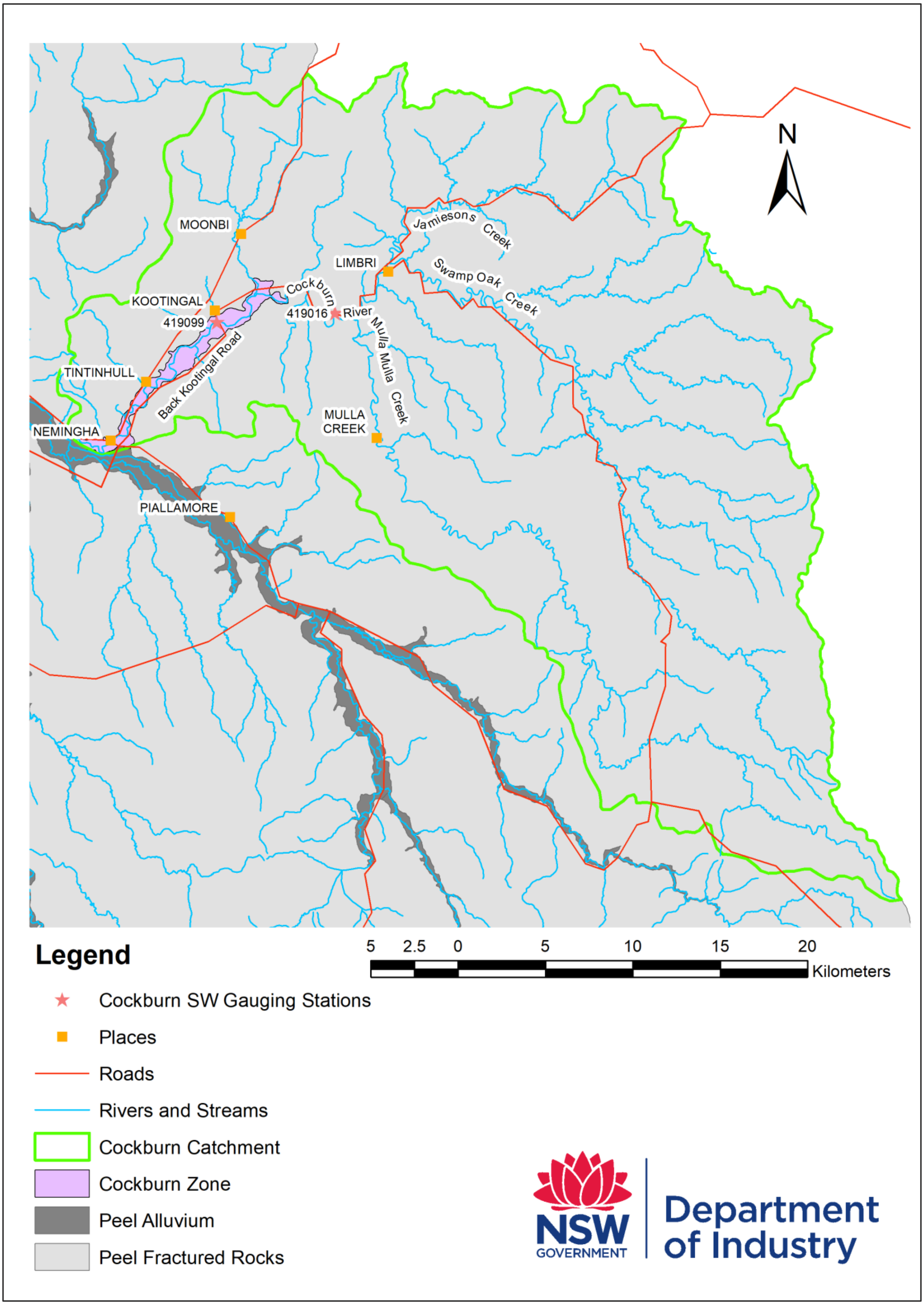

Figure 1: Location Map

2.4. Groundwater Entitlement and Usage

Table 1 summarises the groundwater access licences and entitlement in the Cockburn Zone. The total groundwater entitlement is 4,720 ML. Groundwater usage is metered for each production bore.

Table 2 shows the total metered extraction of groundwater from the Cockburn Zone over eight irrigation seasons from 2010-11 to 2017-18. Total surface water entitlement is 3,272 ML however usage is not metered.

Table 1: Number of groundwater licences in the Cockburn Zone

Category of access licence	Number of licences	Entitlement
Local Water Utility*	1	530 ML
Domestic and Stock [Domestic]	2	55 shares
Aquifer	34	4,135 shares

Note: *Local Water Utility entitlements increased from 400 to 530 ML on 15/07/2015

Table 2: Metered groundwater extraction in the Cockburn Zone in ML.

Year	2010-2011	2011-2012	2012-2013	2013-2014	2014-2015	2015-2016	2016-2017	2017-2018
Extraction (ML)	768	784	1,267.6	1,306	1,136.3	1,042.1	499.3	585

Groundwater extraction in the Cockburn Zone has been significantly less than the total entitlement over the period since the commencement of the Plan. Usage since 2012-2013 to 2015-2016 has been above the estimated average annual rainfall recharge of 917 ML. The average extraction since the commencement of the Plan of 924 ML/year, is above the average estimated annual rainfall recharge.

2.5. Effect of Plan Cease-to-Pump Rules on Water Access

The surface water cease to pump rules came into force at the commencement of the Plan. The groundwater cease to pump rules were scheduled to commence four years after the commencement of the Plan, i.e. July 2014, however, due to some implementation issues, these were formally deferred until the seventh year of the Plan (July 2017) to allow for a review of the access rules to be conducted.

Table 3 and **Figure 2** show the number of days and the periods of surface water cease to pump enforcement, and illustrate how the groundwater cease to pump rules would have hypothetically affected groundwater access, had they been implemented, based on recorded flows over the period of the Plan. The data shows that there was an increase in the level of groundwater usage in years when the surface water cease to pump rule was triggered. Groundwater use was highest in the year of lowest river flows (2013-2014). This demonstrates that groundwater is an important replacement resource at times of low surface water availability.

Table 3: River flows, cease to pump periods and groundwater use since commencement of Plan.

Water Year	River flow at Mulla Crossing GS ML	River flow at Kootingal Bridge GS ML	No. days surface water cease to pump	No. days groundwater cease to pump	Groundwater Usage ML
2010-2011	137,772	142,802	0	0	768
2011-2012	73,1108	82,347	0	0	784
2012-2013	20,743	24,935	137	(51)*	1,267.6
2013-2014	2,148	1,835	296	(212)*	1,306
2014-2015	16,103	15,228	196	(70)**	1,136.3
2015-2016	36175	38413	185	(100)**	1042.1
2016-2017	88,322	88,959	34	0	499.3
2017-2018	4,662	4,650	278	(194)	585

* Groundwater cease to pump rules not yet commenced, numbers in brackets indicate days if the rules had applied.

** Groundwater cease to pump days that would have occurred, but cease to pump rules deferred until the 7th year of the plan 2016/2017.

Note: if you consider both the 2017 – 2018 and 2018 – 2019 water years consecutively a cease to pump commenced on the 12-12-2017 and finished on the 21-12-2018 being a total of 375 days.

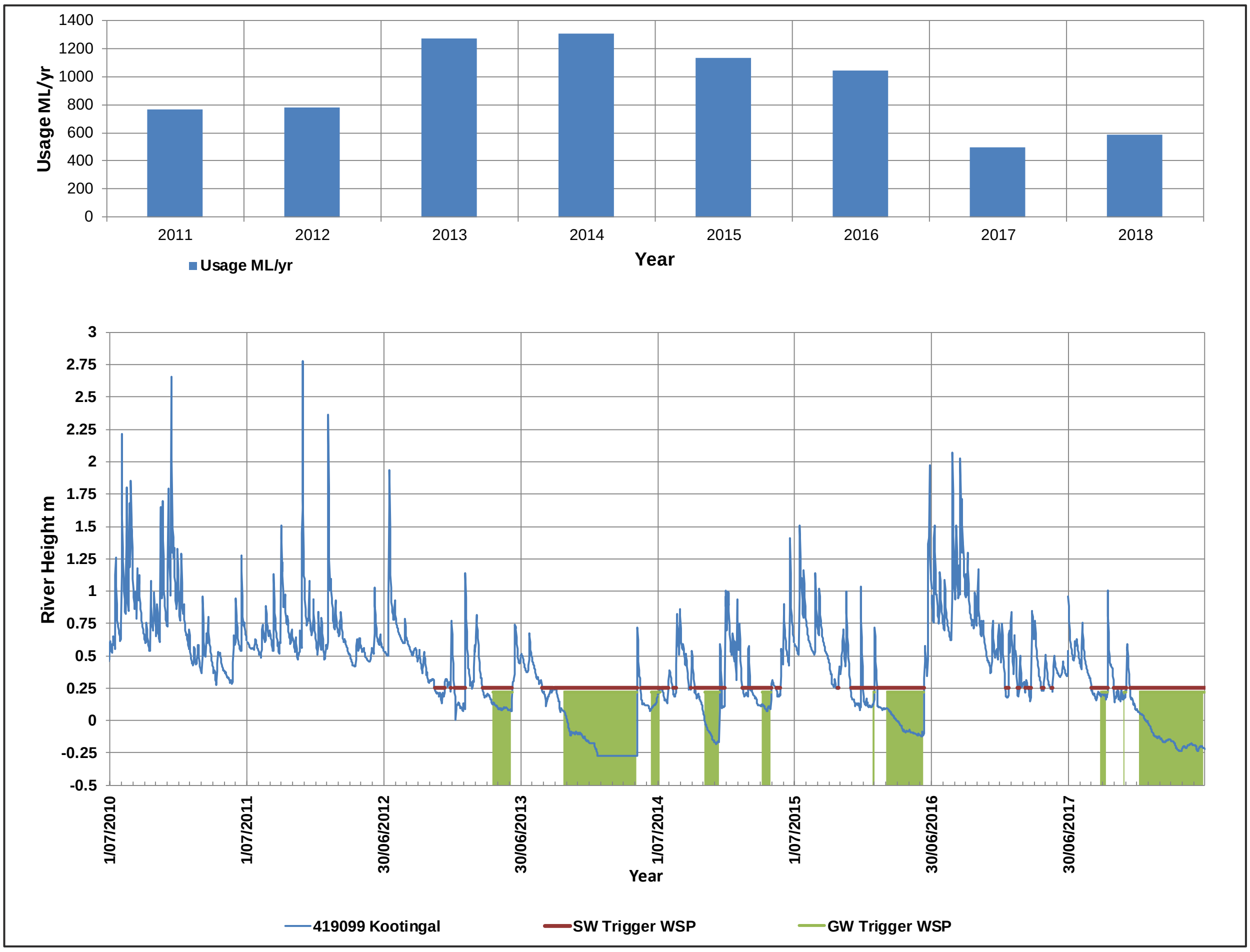

Figure 2: Cockburn River gauge heights and cease to pump periods

3. The Hydrology of the Cockburn Zone

This section provides an overview of the physical characteristics and dynamics of the Cockburn Zone's surface water and groundwater system. This is to support the analysis made in the following sections that investigates how the management rules affect the connected surface water and groundwater resource.

3.1. Rainfall

There are two weather stations with rainfall data near to the Cockburn River Zone; Kootingal (ID55148), and Tamworth Airport (ID 55054 and 55325). The location of the rainfall measuring station at Tamworth Airport was moved in 1992 by about 1.2 km.

An analysis of the rainfall data is provided in **Figure 3**. The cumulative deviation of rainfall from the average provides a very useful visual representation of the rainfall history in the area. A falling trend indicates a period of lower than average rainfall, a rising trend shows periods of above average rainfall.

In more recent times, the chart shows that an extended period of below average rainfall was experienced from the early 1990s to 2007, above average from 2007 to 2014, then below average in 2015, above average in 2016 and below average since 2017.

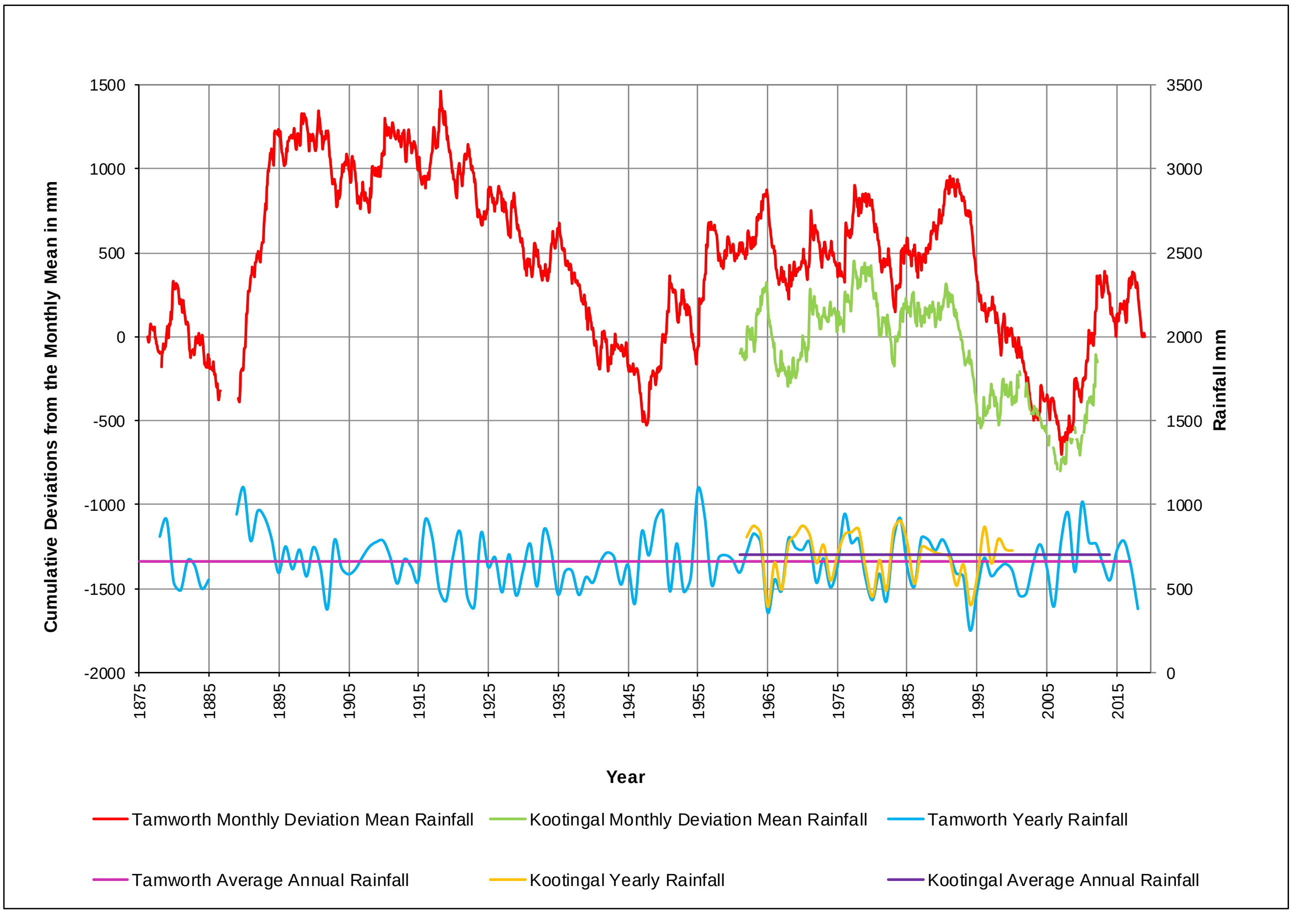

Figure 3: Rainfall cumulative deviation from the mean

3.2. Cockburn River

The Cockburn River is a tributary of the Peel River, located in northern NSW as shown in **Figure** 1. The Cockburn River commences at the confluence of Jamieson Creek and Swamp Oak Creek about 500 metres upstream of Limbri. The Cockburn River then flows in a south westerly direction until its confluence with the Peel River at about 3.6 km downstream of Nemingha.

There are two current river gauging stations on the Cockburn River; Kootingal Bridge (GS419099) and Mulla Crossing (GS419016). Their locations are shown in **Figure 1**. River flow (discharge) and height (level) have been recorded at Kootingal Bridge from February 2006 to present. At Mulla Crossing, discharge has been recorded since 1936 to present and level from 1973 to present.

Error! Reference source not found. charts the discharge (flow) of the Cockburn River at the two locations since 2006. Peak flows are greater at Kootingal Bridge than Mulla Crossing due to inflow from small tributaries between the two locations.

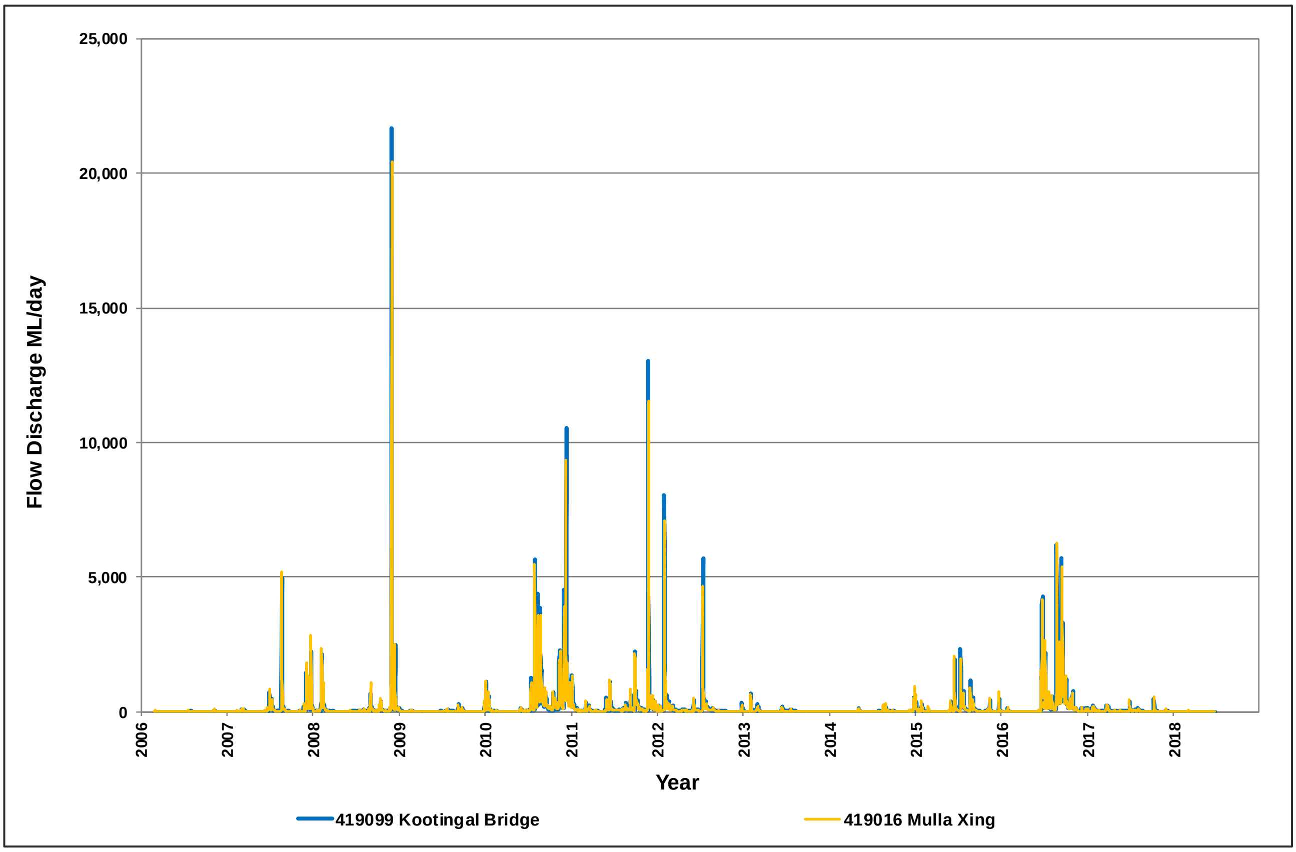

Figure 4: River Hydrographs

Flow data is summarised in **Table 4**. This indicates that whilst the maximum daily flow at Kootingal Bridge has been greater than at the Mulla Crossing since 2006, the median flow at Mulla Crossing is greater. This suggests that the river loses flow between these locations during lower flow conditions.

Table 4 Cockburn River Flow Statistics

Discharge (ML/day)	Kootingal Bridge	Mulla Crossing (1936 – present)	Mulla Crossing (2006 – present)
Maximum	21,692	51,439	20,426
Minimum	0	0	0
Average	109	208	100
Median	7	12	27

The time weighted discharge rate duration curves for the two gauges are shown in **Figure 5** and **Figure 6** for the period from 2006 to June 2018. The charts show that river flow occurs at Kootingal Bridge 84% of the time and at Mulla Crossing 87% of the time during this period. For the full period of record at Mulla Crossing, i.e. since 1936, the river flows 94% of the time. This indicates that river flows have been lower and less reliable over the shorter period since 2006 than over the longer term.

Although at times there is no measurable flow at the Kootingal Bridge, the river does not dry up completely and is present as a chain of interconnected pools that are maintained by groundwater discharge to the Cockburn River.

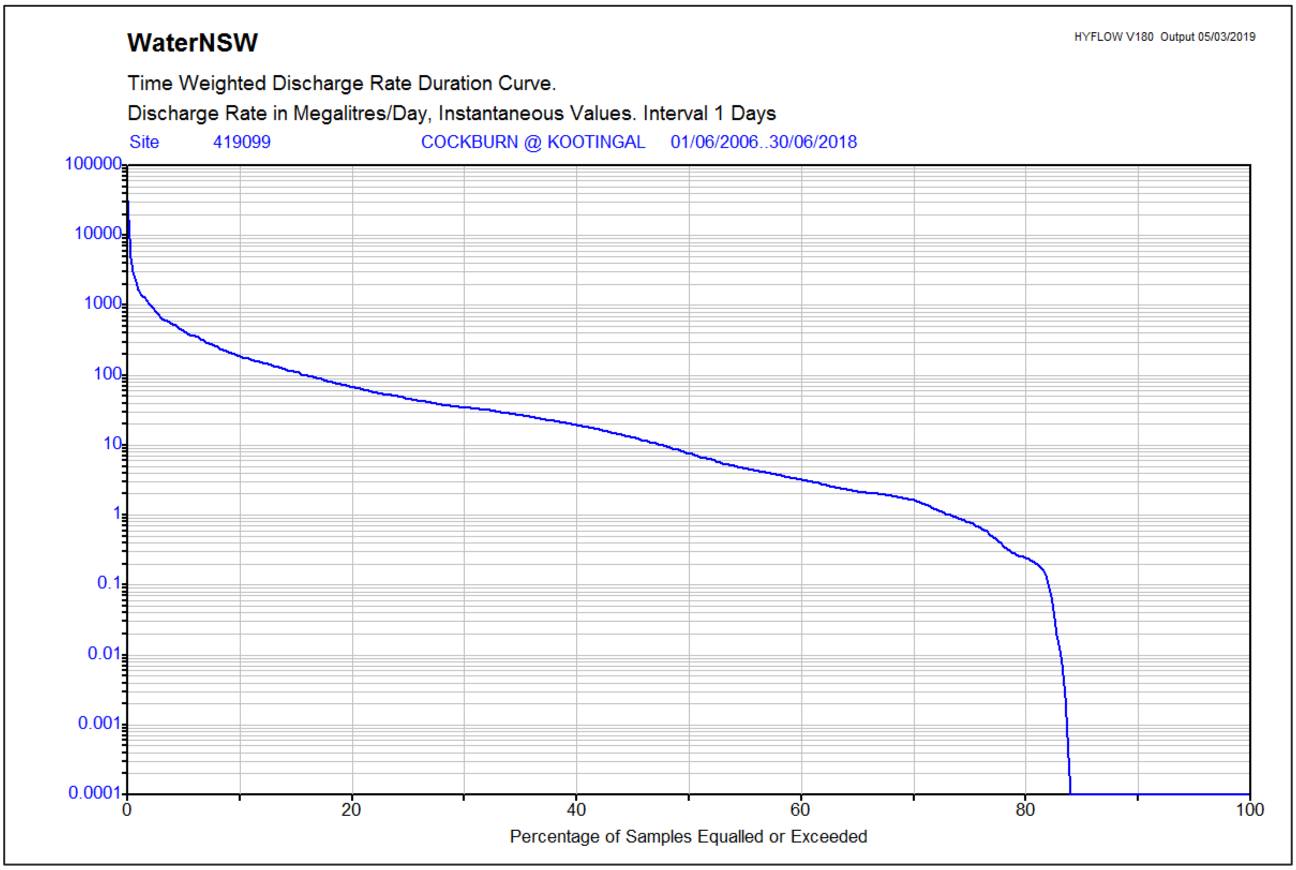

Figure 5: Kootingal Bridge Flow Duration Curve

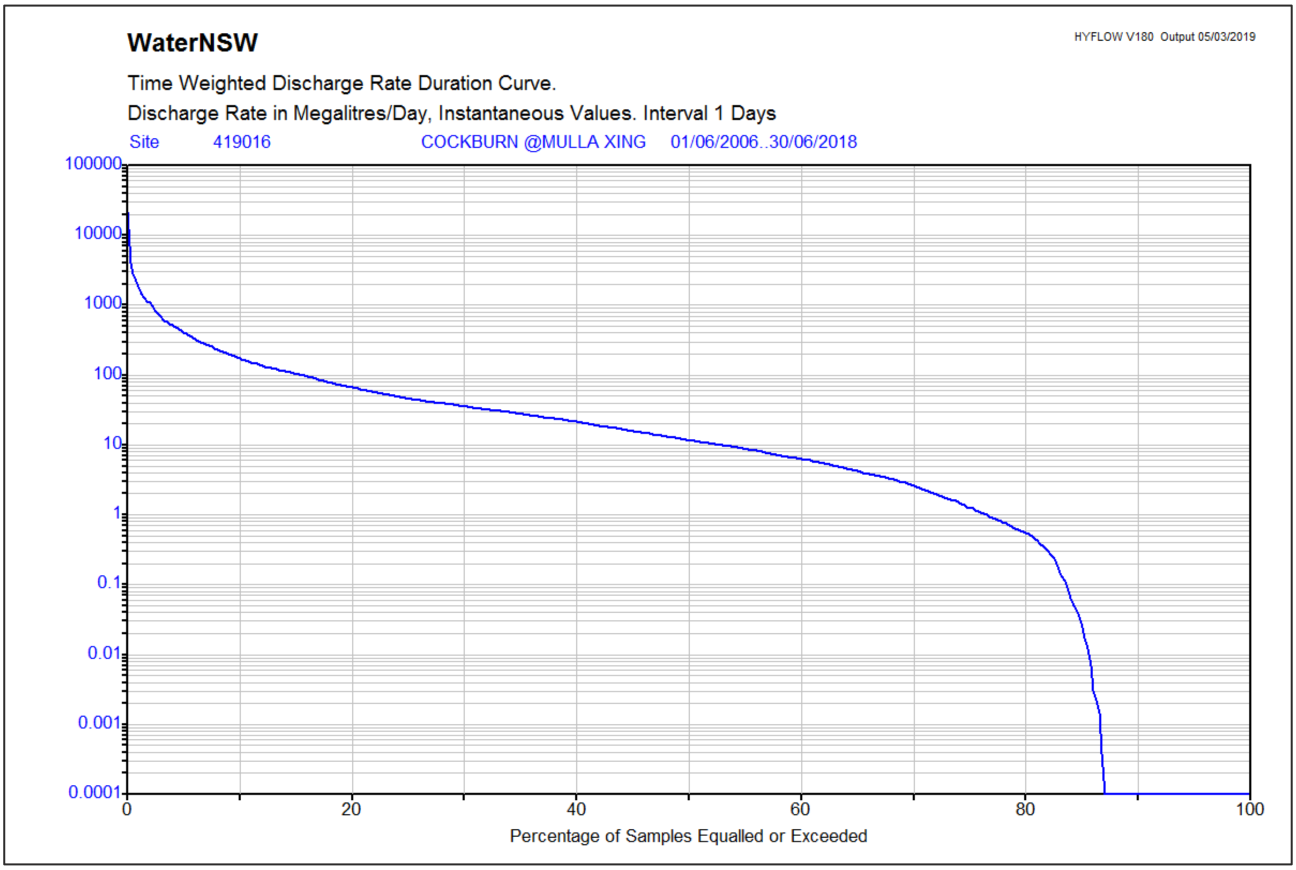

Figure 6: Mulla Crossing Flow Duration Curve

3.3. Hydrogeology

3.3.1. Geology

Upstream of the Cockburn Zone the Cockburn River flows across Palaeozoic metasediments of the Peel Fractured Rock Water Source. These metasediments underlie the alluvial sediments along the Cockburn River which extend from approximately 4.3 km downstream of the Mulla Crossing GS, to approximately 2 km downstream of Nemingha.

The alluvium consists of sands, clays, gravels, cobbles and boulders greater than 200 mm in size in varying proportions. The alluvium thickness is mostly less than 12 m but in some localities it can be up to 20 m thick. The standing water level varies from 4 m to 7 m below the ground surface. The saturated thickness varies from 4 m to 12 m averaging about 6 m thick. The top 3 m to 5 m of the alluvium is generally loam or clay rich soils. The main sand, gravel and cobble layer occurs below the upper soil layer. The bank of the river ranges in height from 5 to 7 m above the average stream flow level (O'Rourke, M. 2010).

3.3.2. Groundwater Hydrology

Recharge

Recharge into the alluvium is from diffuse rainfall falling upon the alluvial plain, river leakage from the Cockburn River and the other small tributaries, and some side slope run on. The Cockburn River is both a source of recharge to groundwater and also receives groundwater discharge as baseflow that enables the river to maintain low flows and pools during dry seasonal conditions. In dry times, when there is little rainfall recharge, tributary flows or side slope seepage, the Cockburn River provides most of the recharge to the groundwater.

Modelling by Broadstock (2009) for the Peel valley used a 10% average rainfall for Tamworth as a generic recharge rate. Applying that to the average annual rainfall at Kootingal of 700 mm/yr yields an estimated rainfall recharge of around 70 mm/yr.

Groundwater Storage

The volume of groundwater in storage can be estimated from the volume of the aquifer (area multiplied by the saturated thickness) and the percentage of space occupied by water between the pore spaces of the aquifer material, known as its specific storage.

The volume of groundwater stored in the Cockburn Zone is estimated to be about **8,000 ML**. This is based on total area of 13,097 ha, an average saturated thickness of 6 m and an average specific storage of 0.1. The saturated thickness is the distance from the water table to the base of the alluvium. It is less than the total thickness of the alluvium and will vary with seasonal conditions.

Transmissivity and Hydraulic Conductivity

Transmissivity (T) and hydraulic conductivity (K) are measures of the rate at which groundwater flows through an aquifer, and can be highly variable from location to location. The transmissivity and hydraulic conductivity estimates have been made of the Cockburn Zone aquifer from analyses of how water level in extraction bores fall in response to groundwater pumping.

As is often typical, results are spatially variable and are affected by assumptions made in the analysis. From a range of 43 to 2,454 m^2/day, the average transmissivity is estimated to be 447 m^2/day. The hydraulic conductivity is simply the transmissivity multiplied by the saturated thickness of the aquifer. Adopting a typical saturated aquifer thickness of 6 m, gives a K of 75 m/day.

Groundwater Through-flow

Through-flow, or flux, is the volume of groundwater that moves through the cross-sectional plane of an aquifer over a given time, typically expressed as megalitres per year (ML/yr). The volume of groundwater flow out of the Cockburn Zone is estimated to be about 460 ML/yr, based on the hydraulic conductivity estimated above.

3.3.3. Groundwater Monitoring

Ten monitoring bores were installed in or adjacent to the Cockburn Zone in 2000. There is a transect of five bores at Kootingal Bridge (**Figure 7** - GW093036 to GW093040) and five near Nemingha (GW093030 to GW093033, GW093031). Drilling shows the Cockburn Zone alluvium ranges from 11 m to greater than 21 m thick.

Groundwater levels have been manually recorded from between fortnightly to monthly intervals since the bores were installed and continuous data recorders with telemetry have recorded water levels in GW093036 and GW093037 since 18 February 2005 and in GW093040 since 11 December 2002, to the present.

The data shows that groundwater flows through the alluvium down valley. The greatest aquifer thickness and consequently the area of greatest through-flow is across the Kootingal section south of the river. The groundwater level is higher on the northern side of the river than on the south side at this location. This indicates the river is both gaining groundwater flows from the north and losing flow to the southern side. Monitoring data from the Nemingha section of bores indicate that the Cockburn River is gaining water from groundwater in the lower sections.

Figure 8 shows the groundwater level data for bores GW093036 to GW093040 and the stream level hydrograph for the adjacent Kootingal Bridge River gauging station (GS419099). This data shows that the trends in groundwater and surface water levels are closely aligned, demonstrating a good connection between the surface water and the groundwater. There is no surface water gauging station near the Nemingha monitoring bores.

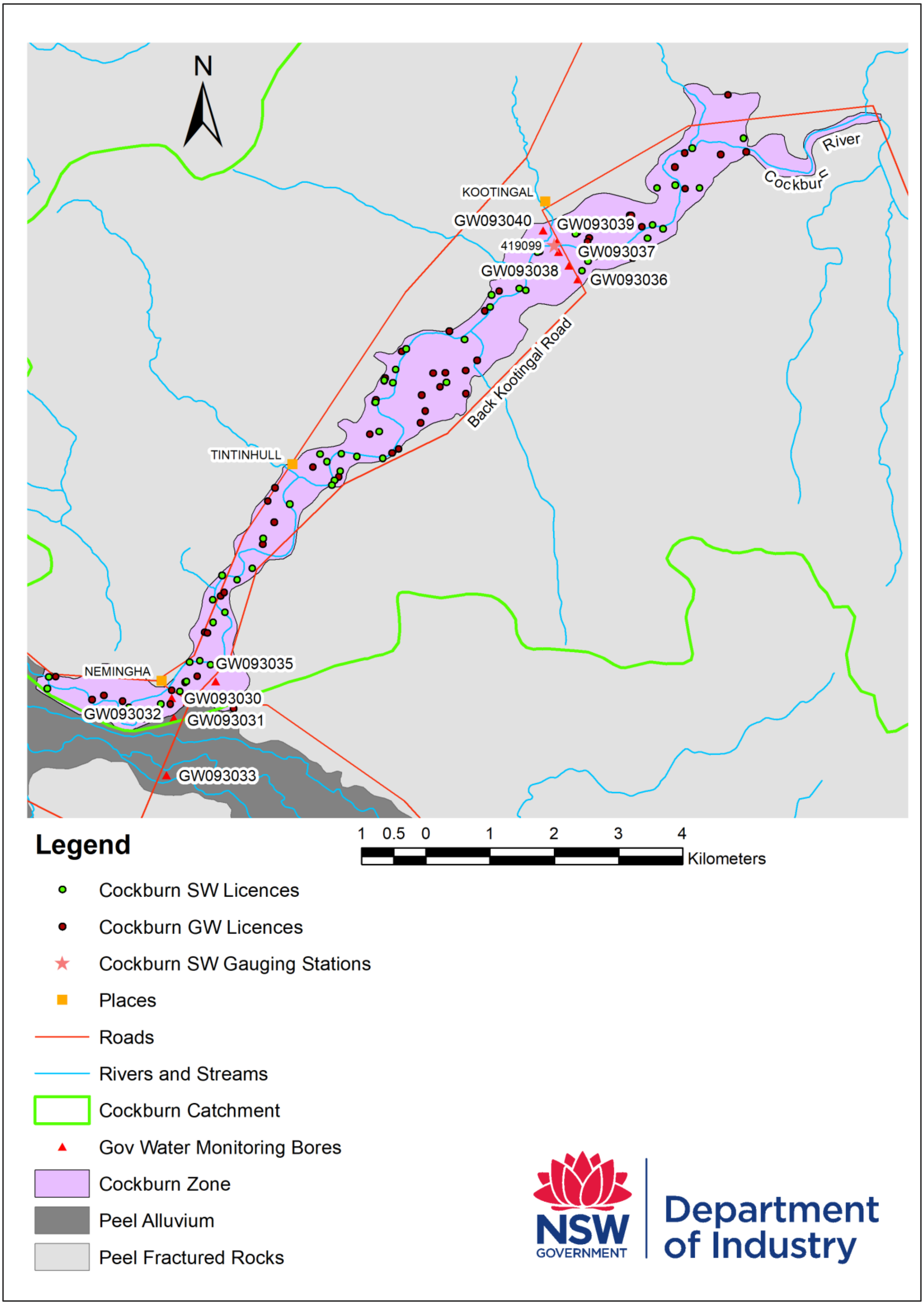

Figure 7: Monitoring Bore Map

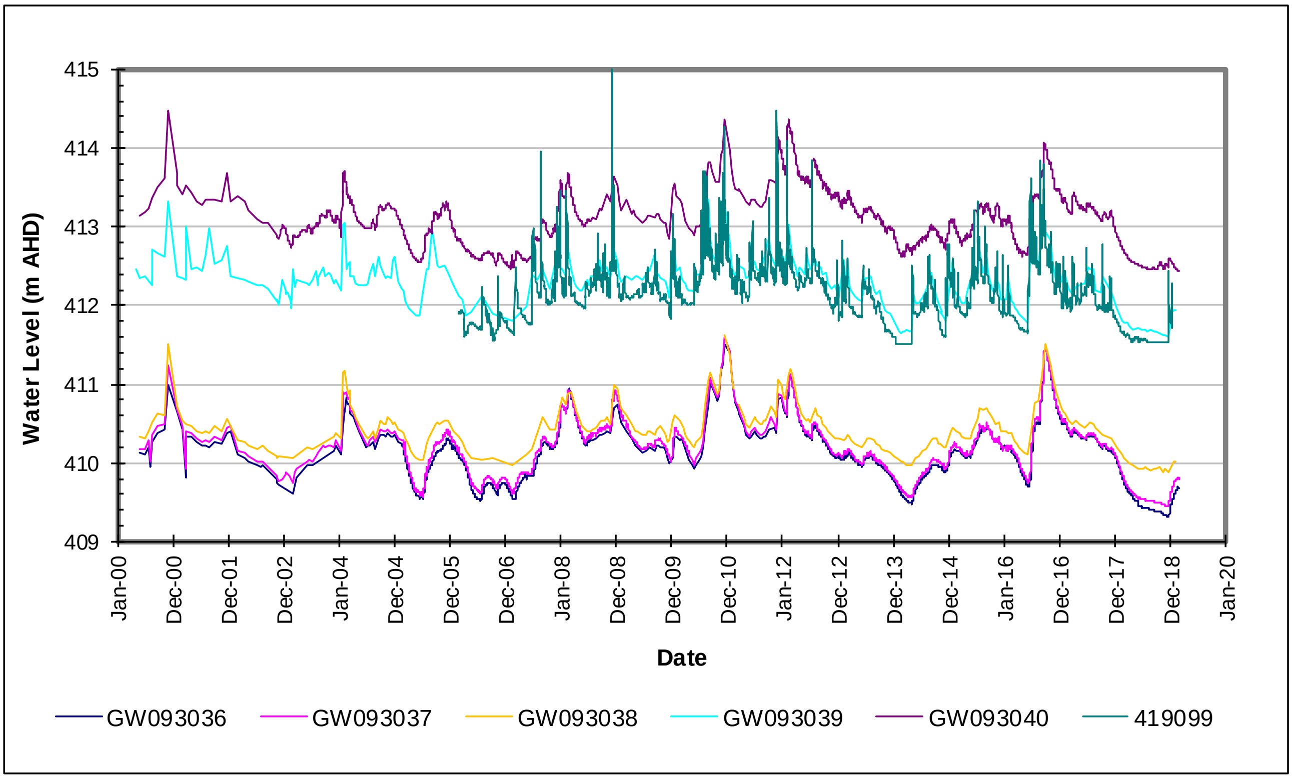

Figure 8: Kootingal GW and SW Hydrographs

3.4. Surface Water-Groundwater Interaction

3.4.1. Conceptualisation of Flow Dynamics

Water enters the Cockburn system through runoff from the surrounding hills and ephemeral creeks that flow onto the floodplain. Much of this overland flow seeps through the highly permeable soils on the floodplain recharging the groundwater. During dry seasonal conditions there would be little tributary flow and/or side slope run on.

The Cockburn River alluvium forms an unconfined aquifer in which groundwater flows down valley under gravity. There is some lateral flow into the Cockburn River at Kootingal, however the predominant flow direction within the alluvium is down gradient through the deeper section of the alluvium to the south of the river.

The interaction between the river and the groundwater varies along the river reaches both spatially and temporally. That is, the river gains baseflow from groundwater discharge where/when the water table is higher than the river level and the river loses water into the alluvium where/when the water table is lower than the river.

The interaction between the river and the groundwater is influenced by the geometry of the alluvium and the path of the river channel. For example, where the floodplain is narrow groundwater flow is restricted and the water table would be higher immediately up stream of the restriction. This would favour extended periods of groundwater discharge to the river at these locations. This would also be the case in areas where the river coincides with areas of shallow alluvium where groundwater flow is restricted by the shallow bedrock.

At the downstream end of the system near Nemingha the gradient of the aquifer is reduced and as a result the groundwater moves through the Cockburn Zone at a slower rate as it nears the confluence with the Peel Alluvium.

Upstream of Nemingha there would be a point at which the river goes from predominantly losing to predominantly gaining. This point will move up and down the valley depending on the seasons, rainfall variability, river flow volume, groundwater level and extraction.

3.4.2. Evidence of Connectivity

The flow duration curve indicates that the Cockburn River flows 84% of the time at Kootingal Bridge (**Figure 5**). Given the duration between rainfall events, this could only be maintained if the river received base flow from the groundwater in addition to surface run off. The presences of pools within the river channel during periods of no river flow also indicates that groundwater through flow is maintaining the pools (Cook *et al*, 2006).

River and bore hydrographs showing the relative height of groundwater levels in monitoring bores near Kootingal Bridge indicate that the hydraulic gradient is both from groundwater to the river and from the river to groundwater at this locality. The variations in groundwater levels also reflect surface water temporal patterns. This relationship is strongest close to the river and weakens with distance from the river. This is true for both the time lag and amplitude of the response.

It is noteworthy that available flow data indicates that in the years when rainfall is high the total river flow is greater at the Kootingal Bridge GS than for the Mulla Crossing GS. However, this is reversed in periods of low river flow. This suggests that in dry seasons the lower river flows at Kootingal are likely to be influenced by the river losing more water into the alluvium due to the lower water table conditions and the higher levels of water extraction from both the river and groundwater.

Further studies confirm the prevalence of water exchange between the river and aquifer. Berhane et al (2008) and Berhane (2015) used water temperature differences to demonstrate that some reaches of the Cockburn River were losing and other reaches were gaining. Cook *et al* (2006) used water radon gas concentrations to conclude that groundwater flowed into some sections of the river but not others. The later study calculated that the net groundwater inflow to the Cockburn River was approximately 0.048 m^3/s across its full length. This equates to 4.15 ML/day or 1,515 ML/yr compared with a median flow rate of 6 ML/day at Kootingal Bridge

4. Assessment of Impacts of Groundwater Extraction on the Cockburn River

The impacts of groundwater extraction on a river are dependent on:

- the location and rate and duration of pumping from a groundwater extraction point;
- whether the stream is gaining or losing , and
- the aquifer’s storage and hydraulic properties.

Groundwater extraction can impact on a river by either capturing baseflow (i.e. groundwater that would otherwise flow into the river) or by inducing additional river leakage. The magnitude of impact can be estimated by various methods using a range of assumptions that provides insights that assist the consideration of potential management options.

Groundwater extraction impacts on a river can be attributed to short term pumping impacts during an irrigation season, and longer term changes to the groundwater storage over successive years. For the purposes of this report only the short term impacts are being considered here.

In a dynamic connected groundwater system such as in the Cockburn Zone, groundwater pumping will impact on river flows by altering the relative components of the overall water budget. To understand this, an analysis of the components of the water budget in the Cockburn Zone is discussed here. The driest year since the implementation of the Plan (2013-14) has been chosen to examine a period when the groundwater components of the water budget are largest compared to surface water. This allows us to understand system dynamics when impacts from groundwater extraction are likely to be at the higher-end of a range. An overall water budget for the year is firstly presented followed by modelled volumetric estimates of groundwater extraction impacts.

4.1. Cockburn System Water Budget for Water Year 2013-14

An overview of the groundwater budget for 2013 – 2014 water year is shown in **Table 5.** Volumes are presented for the whole year, and for the period of enforcement of the surface water cease to pump rules (28/9/2013 to 7/5/2014).

During a dry year the run on from side slopes and the tributaries onto the floodplain is expected to be minor and the relative proportion of rainfall reaching the water table is also likely to be lower than average given that the soil profiles would be very dry. A high-end estimate of 10% of the rainfall for 2013 -2014 has been used to estimate diffuse rainfall recharge and run on contributions in that year. This equates to an approximate annual rainfall recharge of 543 ML. For the period of the surface water cease to pump the rainfall recharge is estimated to be about 398 ML. Over the full water year, total groundwater outflow is estimated to be 1,766 ML (1,306 pumped plus 460 ML through flow). These volumes are significantly greater than recharge, hence groundwater is being removed from storage and the water tables are lowering.

Gauging data shows the Cockburn River losing flows to groundwater upstream of Kootingal with a difference in flow (i.e. loss) of 312 ML. This net loss represents 15% of the total river flows at Mulla Crossing. This measured loss in flow does not necessarily equate to an equivalent gain to groundwater as pumping from the river and evaporative losses (including evapo-transpiration from riparian vegetation) would also be occurring.

For the 222 days (from 28 September 2013 to 7 May 2014) that surface water licence holders were not permitted to pump, the total flow at Mulla Crossing GS was 477 ML and total flow at Kootingal Bridge GS was 82 ML indicating a loss of 395 ML, or 83% of the river flows at Mulla Crossing during that period.

The volumes of groundwater extraction and losses in groundwater storage are significant when compared to the total river flows, particularly during the surface water cease to pump periods. In a whole-of-system sense this indicates that ongoing groundwater extraction during dry spells that trigger surface water cease to pump conditions are likely to further exacerbate reduced surface water flows.

Table 5: Cockburn Zone Water Budget, Water Year 2013-14

Budget Element (ML)	2013-14 Water Year	CTP (28/9/13-7/5/14)
Est. Rainfall Recharge	**543**	**398**
Total river flow Mulla Crossing	**2,147**	**477**
Total river flow Kootingal Bridge	**1,835**	**82**
Groundwater Extraction	**1,306**	**722**
Groundwater throughflow	**460**	**280**

4.2. Modelled Impacts of Groundwater Extraction for Water Year 2013-14

An analytical model for estimating stream depletion from groundwater extraction based on a solution developed by Swamee, Mishra and Chahar (2000) was used to provide an indication of the expected volumetric impact of groundwater extraction on the Cockburn River.

Table 6 summarises the modelling undertaken and the results obtained, and is presented in three parts. The left-most four columns show the groundwater extraction points used in the model including extraction volumes, rates and the distance of each extraction point from the river. The centre six columns show the daily river losses simulated by the model for each extraction point at various times since modelling commenced. The final six columns show the simulated cumulative volumetric losses from the river induced by each extraction point, at various times since the simulation commenced.

Eleven of the highest-use bores/wells in the Cockburn Zone were chosen to analyse the potential impacts for the 2013-2014 water year – three are Local Water Utility (LWU) bores and eight are used for irrigation. Together the extraction from the 11 bores/wells equates to 67% of the total metered extraction for the Cockburn Zone (thus provides only a partial representation of the impacts of groundwater extraction).

The modelling scenario assumes the LWU wells pump throughout the water year and irrigation extraction commences from 1 December. The LWU bores pumped 164.7 ML prior to 1 December (184 days). During this time the cumulative impact of pumping from the LWU bores is modelled to be 134 ML.

The modelling assumes that all irrigation commences on 1 December and the bores pump continuously for 100 days. Total extraction from the eight irrigation bores is 791 ML. The LWU wells pump a further 89 ML for the same period.

Daily loss volumes for each extraction point, and totals across all 11 bores, are shown in **Table 6** at 14, 28, 50, 75 and 100 days after the commencement of pumping. The total daily losses are plotted in **Figure 9** and show that daily losses increase with time, although the rate of increase decreases over time. At 100 day, total daily river losses induced by groundwater extraction are just under 5 ML/day.

Cumulative total river losses for each extraction point, and totals for all 11 bores, are shown in **Table 6** at 14, 28, 50, 75 and 100 days after the commencement of pumping. The cumulative losses are plotted in **Figure 10** and show close to a linear trend. After 100 days of irrigation extraction plus the pumping from the LWU bores, the total cumulative loss from the Cockburn River is over 500 ML.

This volume is very significant when compared to the flows measured in the Cockburn River in the same water year. The water budget in **Table 5** shows total flows at Mulla Crossing and Kootingal Bridge to be 2,147 ML and 1,835 ML respectively over the whole water year, and 477 ML and 82 ML respectively across the surface water CTP period. The modelling shows that groundwater extraction during a dry water year such as 2013-14 has significant impacts on surface water flows.

Table 6: Estimated impacts of groundwater extraction on the Cockburn River for 2013-14 water year

Type	Pumped volume	Rate	Distance *	Induced daily volume loss from river at day 0, 14, 28, 50 75 and 100 (ML/day)						Total volume loss after 0, 14, 28, 50 75 and 100 days of continuous pumping (ML)					
	ML	L/s	m	Day 0	Day 14	Day 28	Day 50	Day 75	Day 100	0 Days	14 Days	28 Days	50 Days	75 Days	100 Days
Irrigation	51.4	5.9	250	0	0.14	0.21	0.27	0.31	0.33	0	1.09	3.68	9.1	16.36	24.34
Irrigation	63.4	7.3	485	0	0.04	0.10	0.17	0.22	0.26	0	0.2	1.24	4.34	9.31	15.36
Irrigation	65.6	7.6	305	0	0.13	0.22	0.30	0.35	0.38	0	0.91	3.52	9.4	17.57	26.76
Irrigation	74.5	8.6	485	0	0.05	0.12	0.20	0.26	0.30	0	0.24	1.47	5.11	10.97	18.09
LWU	24.1	2.79	180	0.19	0.19	0.19	0.2	0.2	0.2	29.67	32.38	35.11	39.44	44.41	49.43
Irrigation	114.5	13.3	42	0	0.95	1.01	1.04	1.06	1.07	0	11.82	25.62	48.23	74.53	101.2
LWU	32.5	3.76	50	0.31	0.31	0.31	0.31	0.31	0.31	53.33	57.61	61.9	68.66	76.37	84.89
LWU	32.9	3.81	75	0.3	0.3	0.3	0.3	0.3	0.31	51.1	55.31	59.54	66.2	73.8	81.43
Irrigation	126.5	14.6	418	0	0.13	0.27	0.42	0.52	0.59	0	0.7	3.64	11.42	23.26	37.2
Irrigation	144.6	16.7	530	0	0.07	0.19	0.34	0.46	0.54	0	0.31	2.2	8.23	18.34	30.88
Irrigation	150.9	17.5	437	0	0.13	0.30	0.47	0.60	0.68	0	0.72	3.92	12.67	28.18	42.24
Average	**101.6**	**11.8**	**314**	**0.07**	**0.22**	**0.29**	**0.37**	**0.42**	**0.45**	**12.19**	**14.66**	**18.35**	**25.71**	**35.74**	**46.53**
Total	**1,118.1**	**129.3**		**0.80**	**2.44**	**3.22**	**4.02**	**4.59**	**4.97**	**134.1**	**161.29**	**201.84**	**282.8**	**393.1**	**511.82**

* Distance of bore from Cockburn River

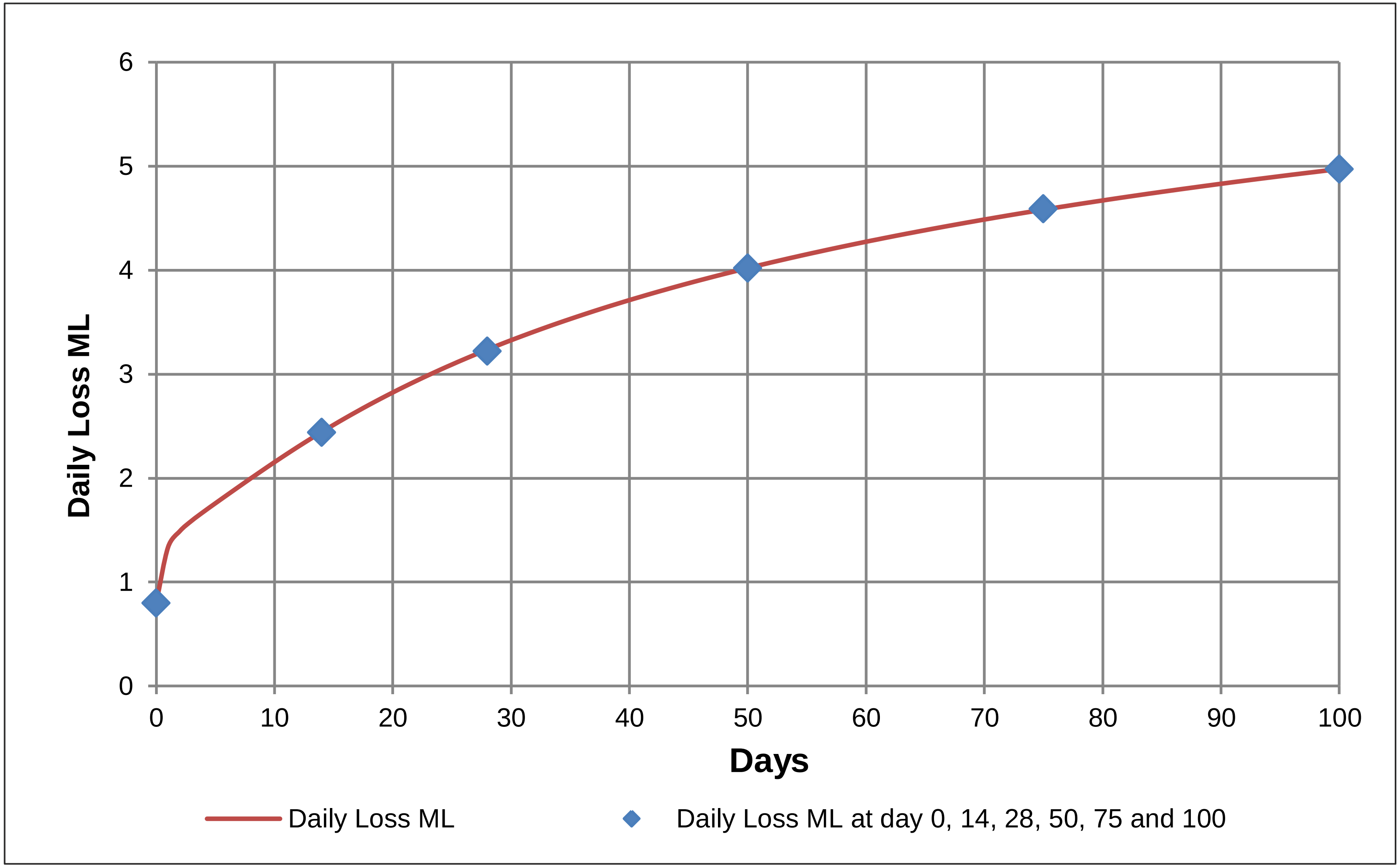

Figure 9: Daily river losses due to groundwater extraction over the 100 day extraction period

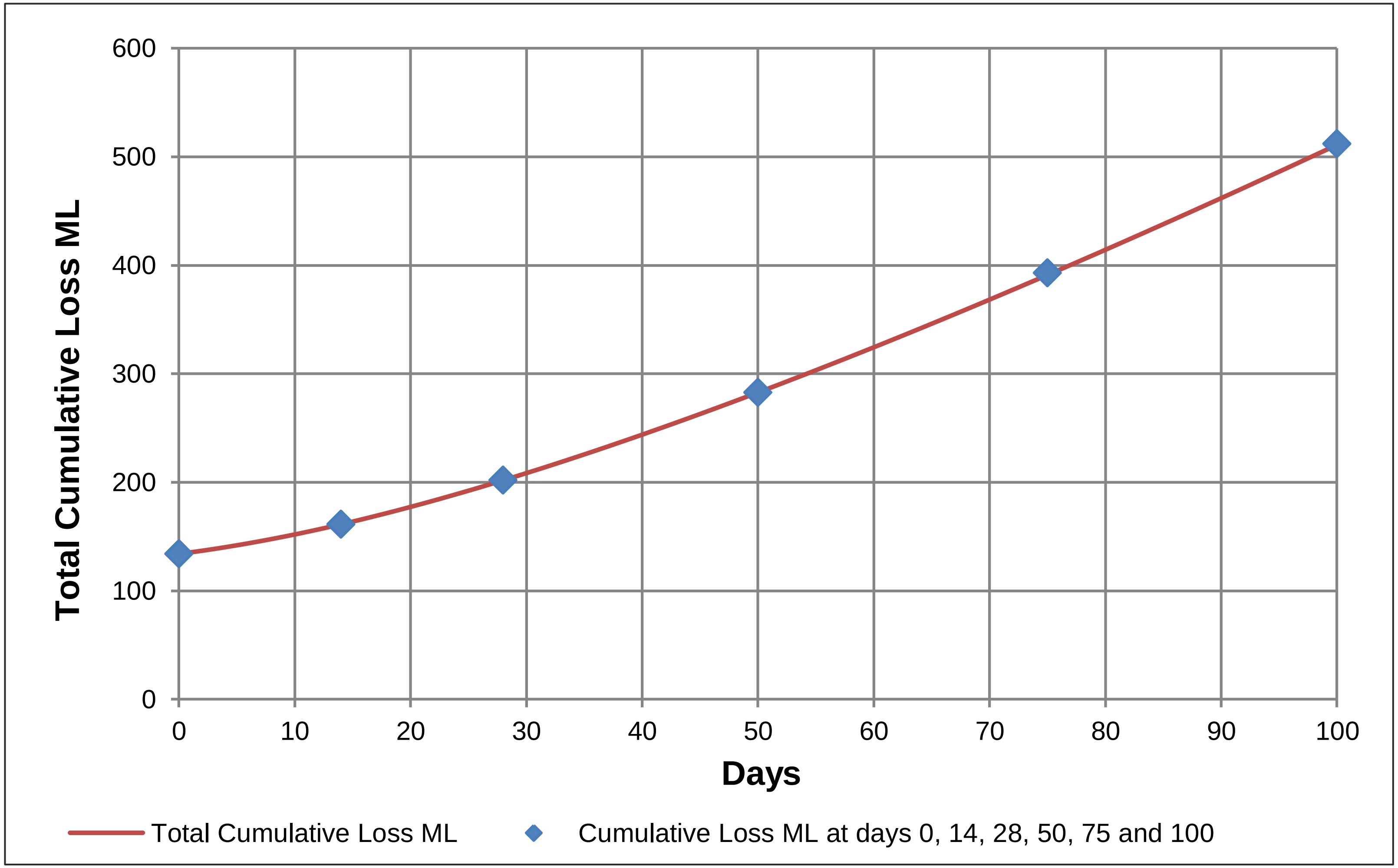

Figure 10: Cumulative (total) river losses due to groundwater extraction over the 100 day extraction period

4.3. Previous Modelled Assessment of Impacts

Broadstock (2009) considered the potential impacts of groundwater pumping on the Peel River, including the Cockburn River tributary, using a simple uncalibrated numeric model. This modelling work considered the effect of varying aquifer parameters, extraction rates and distances from a river with its focus on pumping impacts on the river. The impacts were modelled over one year under average rainfall conditions.

Scenarios applied to the unregulated tributaries (including the Cockburn River) modelled the fall in the river stage height due to pumping.

Figure 11 shows the modelled change in the river stage with time when pumping 1,000 m^3/day (11.6 L/s) at a range of distances from the river under average rainfall and run off conditions. This pumping rate is comparable to the reported average extraction rate of 830m^3/day (9.6L/s) in the Cockburn Zone although it is much less than the reported maximum of 1,860m^3/day (21.5L/s).

Although this modelling work did not specifically model the time lag of impacts on the river when pumping ceases, it does suggest that groundwater extraction at comparable rates to those within the Cockburn Zone does result in a drop in the river stage.

This modelling simulates more favourable conditions than those under which the current cease to pump rules would occur. The modelled scenarios are under average rainfall and run off conditions. If the recharge components of the model inputs were reduced to simulate dry seasonal conditions, then groundwater pumping would have a greater impact on the river as the modelled replenishment rate from rainfall recharge into the groundwater storage would be much less.

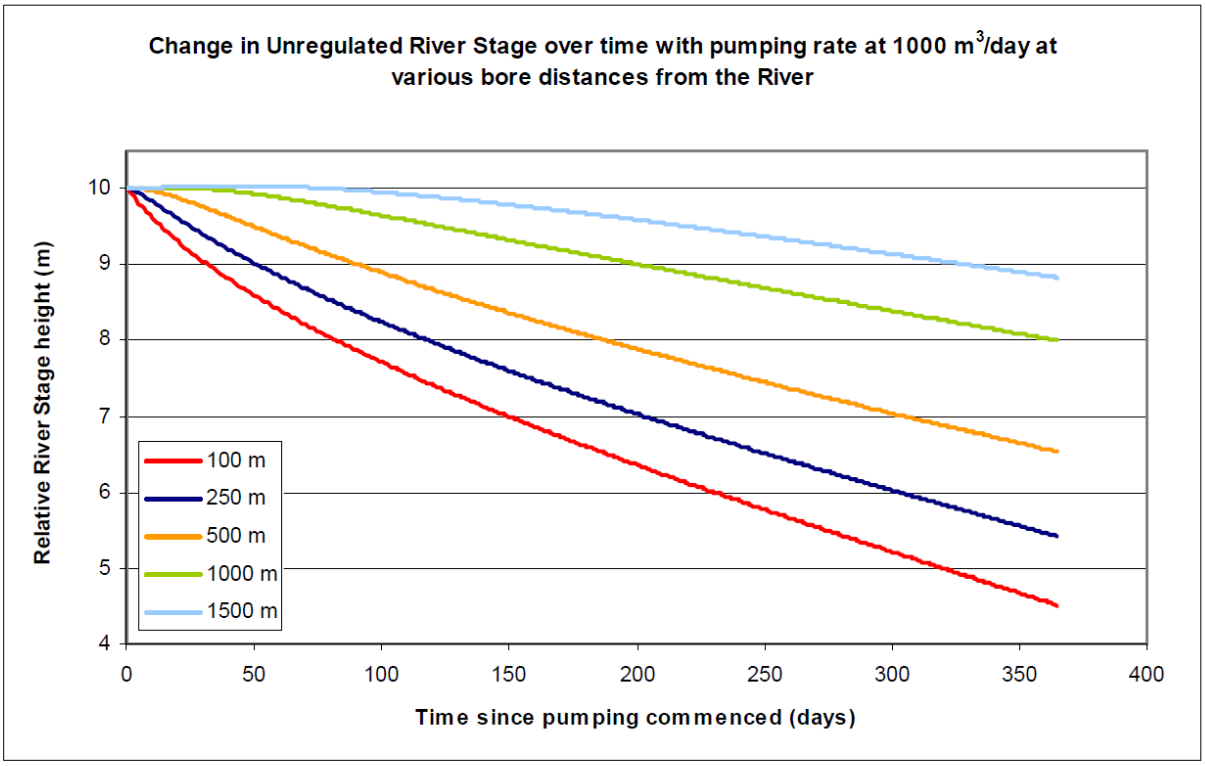

Figure 11: River stage change as a function of distance for a pumping rate of 1,000 m3/day (from Broadstock 2009)

5. Alternative Cease-to-Pump Reference Points

The Kootingal Bridge gauging station is currently used as the cease to pump reference point in the Plan.

There has been concern that the gauging station at Kootingal Bridge may be unsuitable as the cease to pump gauge due to the potential gauging inaccuracies created by the shifting bed of the river. Various suggested solutions include:

- moving the gauge to a position where the stream bed is more stable
- using the Mulla Crossing GS
- using groundwater levels from one of the groundwater monitoring bores

An analysis of river height data shows there is little correlation between the two surface gauging stations in times of low flow. Historical data demonstrates that the Kootingal Bridge GS results in fewer days of restricted access under the current rules than the Mulla Crossing GS under the previously proposed cease to pump rules considered during Plan development. Hence the Mulla Crossing GS is considered inappropriate for an alternative CTP reference point.

The monitoring bores along the Kootingal Bridge section (**Figure 7**) are the only suitable potential sites for considering a groundwater level cease to pump trigger. Bores GW093036, GW093037 and GW93040 are equipped with telemetered data loggers. Hydrographs show that groundwater level changes are too subdued and delayed compared to river heights to be suitable cease to pump reference points.

Bore GW093039, which is located closest to the river near the Kootingal GS is manually monitored fortnightly. Groundwater levels at this location appear to not be sufficiently responsive to river flows to be suitable, although this is difficult to ascertain from data taken only fortnightly. An option exists to equip the bore with a logger and review continuous data after a range of seasonal conditions had been experienced. This would likely require in the order of 2- 5 years of additional data.

Consequently in the short term there are no suitable bores that could be used as cease to pump reference locations however the option may be more viable in the medium to long term.

6. Conclusions

The hydrology of the Cockburn Zone presented in Section 3 supports the concept that groundwater in the alluvial aquifer is highly connected to the surface water of the Cockburn River. River flow duration curves and river and groundwater hydrographs provide qualitative evidence of hydraulic connection between surface water and groundwater. The geometry of the river and aquifer conform to the physical requirements that established the Cockburn Zone as highly connected: the water table is shallow and the alluvium is thin and narrow.

A number of approaches have been described above (Section 4) to assess the potential impact of groundwater extraction on Cockburn River flows. Due to the limited volume of water stored in the alluvium compared to the total groundwater entitlement, groundwater extraction represents a significant potential impact on the Cockburn River if extraction nears full entitlement levels.

It is known that once groundwater pumping has commenced for an irrigation season, there is a delayed impact on the river which is variable based on the distance of the bore from the river and the time since that bore commenced pumping. The Plan rules permit groundwater licence holders to continue to pump for a further 28 days once the trigger for cease to pump on the surface water licence holders has been reached. It has been shown that some level of impact from groundwater pumping was already occurring prior to the river cease to pump being reached. Hence, the impacts of groundwater extraction for a further 28 days after this point will be cumulative.

The groundwater access rules in the Plan are intended to protect the pools in the river during dry seasons as they provide identified habitat for fish (Boys et al 2011). The current groundwater and river flow monitoring programs indicate that the river flows and in-river pools are sustained by groundwater baseflows. That is, groundwater extraction has the potential to impact on the river flows and pool volumes. Managing impacts from groundwater pumping on the river is therefore an integral part of managing the pools for environmental purposes during dry periods.

An investigation of possible alternative cease to pump trigger points has found no currently suitable bores thus no short term alternative; however if equipped with a logger and after 2-5 years of continual data, bore GW093039 may be considered.